

SPECIFICATION

Electronic Version 1.2.8

Stylesheet Version 1.0

SYSTEM AND METHOD FOR MEASURING CIRCUIT PERFORMANCE DEGRADATION DUE TO PFET NEGATIVE BIAS TEMPERATURE INSTABILITY (NBTI)

Background of the Invention

[0001] Field of the Invention

[0002] The present invention relates to a test device and method for measuring the true effects of negative bias temperature instability (NBTI) of PFETs (p-channel field effect transistors).

[0003] Description of the Related Art

[0004] High performance PFETs (p-channel field effect transistors) with p+ polysilicon doped gates have been found to exhibit an instability after voltage/temperature aging. This phenomenon is known as "negative bias temperature instability" (NBTI). The instability occurs under negative gate voltage and is measured as an increase in the magnitude of threshold voltage of the device. Higher stress temperatures produce more degradation. The mechanism is known to cause reliability performance degradation for the PFET because of this change in threshold voltage.

[0005]

Several physical models have been proposed in the literature. Basically, an electro-chemical reaction presumably occurs in the gate oxide, due to sensitivity of p+ gates to moisture trapping. The result is a net positive charge in the gate oxide, causing a

bias effect that affects threshold voltage.

[0006] The degradation caused is exponential with oxide electric field. This problem is getting much worse with each generation of CMOS scaling in which oxide thickness is aggressively scaled down but voltage scaling does not keep pace with the oxide thickness scaling. The mechanism, therefore, becomes a major technology reliability scaling problem.

[0007] A relaxation of the degradation has been observed when the DC stress is turned "OFF" following an "ON" stress. Relaxation is a phenomenon known to occur in charge trapping mechanisms.

[0008] A stress bias configuration of the PFET 10 is shown in Figure 1, where a positive voltage 16 is applied to the diffusions 13,14 and the N-well 12 while the gate 15 of the PFET is at ground potential. This stress bias configuration can alternatively be replaced by the configuration shown in Figure 2 where a negative voltage 21 is applied to the gate while all other terminals of the FET are at ground.

[0009] Figure 3 shows the effect of stress on the drain-to-source current versus gate voltage characteristic 30 of the FET 10. The bias temperature aging under the configuration of Figure 1 produces an increase 31 in the absolute value of the threshold voltage ($|V_{th}|$), which in turn causes a decrease in the drain-to-source current (I_d) for a given gate-to-source voltage (V_g). Again, this PFET device instability is usually referred to as a negative bias temperature instability (NBTI) since it requires the applications of a negative gate voltage for the mechanism to be active. The change in threshold voltage and the corresponding decrease in device current could cause signal delay or performance degradation in operating circuits utilizing such devices.

[0010] There are numerous publications dealing with the characteristics, behavior and physics of the NBTI mechanism. From this literature, it is found that the magnitude of change in threshold voltage after stress for a time duration t under gate voltage of V and temperature T is given by:

[0011]

$$|\Delta V_{th}| = A e^{(-\Delta H / KT)} e^{(-\gamma Tox/V)} t^n \quad (\text{Equation 1}),$$

[0012] where $|\hat{V}_{th}|$ is the magnitude of final threshold voltage value after stress minus its initial value before stress; A, \hat{H} , and n are constants (positive values) that are dependent upon the particular technology in question; \hat{H} is referred to as the activation energy; Tox is the oxide thickness, and K is Boltzmann's constant.

[0013] Figure 4 shows a typical behavior of $|\hat{V}_{th}|$ with a straight line relationship (slope = n) versus time on a log-log scale, as predicted by equation (1). The behavior of the NBTI mechanism described in the literature is the DC stress mode where the stress conditions of Figure 1 are applied. This DC stress mode of Figure 1 will be referred to as the "ON" stress condition, and the behavior of $|\hat{V}_{th}|$ in this case is given by equation (1).

[0014] The increase in the absolute value of the threshold voltage due to the NBTI mechanism is a serious technology reliability problem because it leads to performance degradation and subsequent failure of semiconductor integrated chips. Because this mechanism depends on oxide thickness, as shown in the above equation 1, the degradation caused by the NBTI becomes worse as the oxide thickness is reduced (i.e., as CMOS technology scaling continues and as the drive for better performance intensifies). An important aspect of dealing with this problem is the ability to determine the actual impact of this mechanism on the reliable performance of integrated chips where devices are mostly subjected to pulsed voltage conditions rather than DC conditions.

[0015] This is illustrated in Figure 5, which shows a simple CMOS inverter 50 where the input voltage changes from ground potential to a value of V with a period of \hat{T}_m , and the output voltage is the complement of the input. Excluding transient conditions, the PFET of this CMOS inverter is subjected to two stress configurations. The first configuration is when the output voltage is equal to V, i.e., the gate of the PFET is at ground, and this condition is what has been referred to as the "ON" stress condition.

[0016] The second configuration, as shown in Figure 6, is referred to as the "OFF" stress condition, i.e., when the gate 15 of the PFET 10 is at voltage V, one diffusion is also at

voltage V while the other diffusion is at ground. But, as mentioned above, the behavior of the NBTI mechanism is represented by equation (1) as a DC "ON" stress.

[0017] More realistic to the actual operation of the CMOS inverter, the more realistic question is that of asking what happens to the device under conditions of an "ON" stress, followed by an "OFF" stress. Figure 7A (Case 1) shows the behavior of $|\hat{V}_{th}|$ versus time when the PFET is subjected to an "ON" stress (A) for a duration of 20 seconds, followed by an "OFF" stress (B) for a duration of 1200 seconds with measurements of $|\hat{V}_{th}|$ (readouts) at 10 sec, 20 sec, 60 sec., 180 sec., and 1200 sec. (all measured from the start of the "OFF" stress), and then followed by another "ON" stress (A') for a duration of 20 seconds. The magnitude of the stress voltage was 4.2 V, and the stress temperature was 140°C.

[0018] Even though the magnitude of the threshold voltage shift (C) was small under these conditions, it is noticeable that the "OFF" stress following the "ON" stress caused $|\hat{V}_{th}|$ to decrease measurably. Thus, there is some relaxation effect due to the "OFF" stress following the "ON" stress.

[0019] In Figure 7B, the behavior of Case 1 shown in Figure 7A was replotted. This time the effective time (A, A') under "ON" stress condition is indicated on the X-axis of the plot (meaning that all time intervals for "OFF" stress were not included on the X-axis). The Y-axis for $|\hat{V}_{th}|$ of Figure 7B includes the relaxation effect of the "OFF" stress. It is clear that the behavior of the PFET under pulsed voltage conditions, i.e., repeated combinations of "OFF" and "ON" stressing, would be more complicated than the DC model under "ON" stress, and thus it would be extremely difficult to theoretically predict the actual effect of the NBTI mechanism on the performance of CMOS integrated circuits, and to determine the effect of technology scaling and the effect of different processing conditions.

[0020] Thus, a system needs to be developed to determine the impact of the NBTI reliability mechanism on the performance of CMOS integrated circuits, under any conditions of cycle time (\bar{t}_c), which is the sum of the intervals for the "ON" plus "OFF" stresses ($\bar{t}_c = 1/f$, where f is the frequency or performance), duty factor (DF), which is "ON" time relative to cycle time, and technology processing. Prior to the present invention, no such system has been known.

Brief Summary of the Invention

[0021] The present invention solves the above stated problem by introducing a test circuit and method which can be used to measure the impact of NBTI reliability failure mechanism on the performance of CMOS products. As will be explained in more detail below, the present inventors have found that under a series of "ON" and "OFF" stresses, the degradation behavior for the mechanism deviates from that predicted by the DC model. From both the underlying physics and actual bench stressing testing, it has been found by applying an AC-like stressing that a deviation occurs from the DC results. The deviation depends on frequency and duty factor of the AC stress test.

[0022] This invention provides a technology for determining the true and realistic effects of the NBTI mechanism. It is also vital to provide a technology to determine the actual effect and extent of degradation on functional circuits. The test system disclosed as part of this invention also accomplishes this second result. It is, therefore, an object of the present invention to provide a structure and method for accurately measuring the effects of the NBTI mechanism on CMOS.

[0023] It is another object of the present invention to teach a method of investigating the true effects of the NBTI mechanism using DC stress and AC stress testing techniques, either alone or in combination.

[0024] It is another object of the present invention to teach a test circuit and method of investigating the NBTI mechanism by providing the capability to systematically investigate a change in test parameters, including among others, cycle time, duty factor, voltage, temperature, and stress time.

[0025] It is another object of the present invention to teach a method of determining circuit reliability by including measurement of NBTI effects.

[0026] It is another object of the present invention to teach a method of in-line reliability testing of manufactured hardware in which disposition criteria are set up to include NBTI measurements.

[0027] It is another object of the present invention to teach a technology to measure the true effect of NBTI on circuits, thereby providing a bench mark for technology development to gauge the behavior of new process and technology innovations.

[0028] It is another object of the present invention to teach a method of measuring NBTI effects by correlation of a ring oscillator frequency with a shift in threshold voltage of a PFET.

[0029] It is another object of the present invention to teach a ring oscillator having an odd number of circuit elements, each having a programmable delay.

[0030] It is another object of the present invention to teach a ring oscillator having a variable duty cycle.

[0031] It is another object of the present invention to teach a ring oscillator having an odd number of circuit elements, each element being a non-inverting buffer stage.

[0032] It is another object of the present invention to teach a ring oscillator having a feature that oscillation can be started using an input control signal.

[0033] It is another object of the present invention to teach a ring oscillator with elements having a programmable delay and the programmable delay controlled by a binary word input.

[0034] It is another object of the present invention to teach an NBTI test method in which a single PFET is targeted by having a single one of the targeted PFETs incorporated in each stage of a ring oscillator.

[0035] It is another object of the present invention to teach a method of determining the magnitude and behavior of the degradation due to the NBTI mechanism under any desired AC conditions of voltage, duty factor, and frequency of any intended circuit applications.

[0036] It is another object of the present invention to teach a method that permits a determination of the difference between the degradation due to the NBTI mechanism under DC and AC conditions.

[0037] It is another object of the present invention to teach a method to determine the effect of the degradation due to the NBTI mechanism on technology scaling under actual AC operating conditions and from which an optimum and realistic path for technology scaling could be arrived at.

[0038] It is another object of the present invention to teach a procedure and methodology according to which a reliability in-line manufacturing control system is achieved to protect manufactured goods from any undesired degradation due to the NBTI mechanism.

[0039] To achieve the above goals and objectives, as a first aspect of the present invention, described herein is a ring oscillator including an odd number of elements interconnected in a serially-connected infinite loop, each element having an associated programmable delay feature.

[0040] As a second aspect of the present invention, described herein is a test circuit to measure a Negative Bias Temperature Instability (NBTI) effect for PFETs (p-channel MOSFET) by stressing a target PFET component with at least one stress condition, the target PFET component being integrated as a component into the test circuit, the target PFET component having a source, a drain, and a gate, the test circuit including a ring oscillator having an odd number of oscillator elements interconnected serially in an infinite loop, wherein at least one the target PFET component is integrated into the ring oscillator and a test output providing a point to measure at least one parameter of the ring oscillator.

[0041] As a third aspect of the present invention, described herein is a method of testing a PFET (p-channel field effect transistor) by incorporating a target PFET into a ring oscillator having an odd number of elements, performing at least one stress test on the PFET, and measuring at least one characteristic of at least one of the PFET and the ring oscillator.

Brief Description of the Several Views of the Drawings

[0042] The foregoing and other objects, aspects and advantages will be better understood from the following detailed description of a preferred embodiment of the invention with reference to the drawings, in which:

[0043] Figure 1 shows the PFET bias configuration for NBTI "ON" stress;

[0044] Figure 2 shows an alternate bias configuration for the NBTI "ON" stress;

[0045] Figure 3 shows a testing circuit schematic and the threshold voltage shift due to

the NBTI mechanism;

[0046] Figure 4 shows the power law relationship for $|\hat{I}^n V_{th}|$ versus stress time;

[0047] Figure 5 shows a CMOS inverter showing stress conditions for the PFET;

[0048] Figure 6 shows a PFET bias configuration for the NBTI "OFF" stress;

[0049] Figure 7A shows the behavior of $|\hat{I}^n V_{th}|$ versus time when the PFET is subjected to an "ON" stress for a duration of 20 seconds, followed by an "OFF" stress for a duration of 1200 seconds (Case 1);

[0050] Figure 7B shows a replotting of the data in Figure 7A;

[0051] Figure 8A shows the behavior of $|\hat{I}^n V_{th}|$ versus real (actual) stress time for Case 2;

[0052] Figure 8B shows $|\hat{I}^n V_{th}|$ plotted vs the effective time under "ON" stress condition for Case 2, where the time intervals for the "OFF" stress were not included;

[0053] Figure 9A shows the behavior of $|\hat{I}^n V_{th}|$ versus real (actual) stress time for Case 3;

[0054] Figure 9B shows $|\hat{I}^n V_{th}|$ versus effective time under "ON" stress for Case 3;

[0055] Figure 10 shows the AC pulsed stress configuration for the PFET;

[0056] Figure 11 shows $|\hat{I}^n V_{th}|$ versus effective time under "ON" stress for Case 4;

[0057] Figure 12 illustrates an exemplary top-level pulse propagator circuit;

[0058] Figure 13 illustrates the operation of the pulse propagator for three different control settings;

[0059] Figure 14 illustrates the dynamic self-resetting buffer circuit element used in the pulse propagator;

[0060] Figure 15 illustrates the programmable reset delay circuit;

[0061]

Figure 16 shows another exemplary circuit to further expand the level of stress

control while isolating the performance path to only that PFET which is stressed for the NBTI effect;

- [0062] Figure 17 shows an exemplary ring oscillator in which pre- and post-stress frequencies can be compared;
- [0063] Figure 18 shows exemplary samples of such waveforms from the circuit in Figure 17;
- [0064] Figure 19 shows the procedure for the application of PFET DC stress in the ring oscillator circuit and determining of the degradation model constants; and Figure 20 shows the procedure for the application of PFET AC stress in the ring oscillator circuit and procedure for implementation of in-line control on manufacturing hardware.

Detailed Description of the Invention

- [0065] In order to determine the needed features of the subject test system, the effects of cycle time and duty factor on the NBTI degradation mechanism need to be investigated. The following three cases (Case 2 through Case 4) are discussed.

- [0066] Referring first to Figure 8A, the behavior of $|\hat{I}^n V_{th}|$ versus real (actual) stress time is shown for Case 2. Here, an "ON" stress (A) was conducted at a magnitude of stress voltage of 4.2 V, 140Å°C, for a total duration of 180 seconds, with readouts at 20, 60, and 180 seconds. The configuration was then switched to an "OFF" stress (B), still at 4.2 V and 140Å°C, for total duration of 1200 seconds (measured from the start of the "OFF" stress) with readouts at 10, 20, 60, 180, and 1200 seconds. The stress was then switched back to the "ON" condition (A'), at the same voltage of 4.2V and 140Å°C, for a total duration of 180 seconds, with readouts at 20, 60, and 180 seconds. Thus, for the second case the period \tilde{I}_n , which is the sum of the intervals for the "ON" plus "OFF" stresses, was 1,380 seconds. In the first case, \tilde{I}_n was 1,220 seconds. The duty factor for Case 2 was 0.13 versus 0.016 for Case 1. Thus, the duty factor for Case 2 was significantly higher than for Case 1.

[0067]

In Figure 8B the behavior of $|\hat{I}^n V_{th}|$ is plotted vs the effective time under "ON" stress condition (A, A') where the time intervals for the "OFF" stress were not included. From Figure 8A and 8B it is noted that there is a definite relaxation effect, i.e.,

reduction in $|\hat{V}_{th}|$, when the "OFF" stress is applied following the "ON" stress, as was found in Case 1.

[0068] Another significant observation is made for Case 2. In Figure 8B, the behavior of $|\hat{V}_{th}|$ for the first readouts (three readouts, represented by open circles) in Figure 8A and 8B during the "ON" stress, up to and including time at 180 seconds are modeled by a straight line 80 on a log-log scale as predicted by equation (1), with a value $n = 0.31$, which is the time exponent factor for the power law relationship between \hat{V}_{th} and time.

[0069] The three readouts for the "ON" stress following the "OFF" stress (three triangles in Figure 8B), however, show a different behavior. As shown in Figure 8B the straight line model 81 representing the "ON" stress following the "OFF" stress have a steeper slope with a time exponent factor of 0.46 versus 0.31 for the case where the "ON" stress was not proceeded with an "OFF" stress. Thus, the behavior shown in Figure 8B suggests that following the relaxation effect of the "OFF" stress, the steeper slope of the "ON" stress will cause the $|\hat{V}_{th}|$ to exceed the value it would have, had the "OFF" stress not taken place. This complicated behavior raises a legitimate question regarding the actual behavior for $|\hat{V}_{th}|$ under repeated application of "ON" and "OFF" stressing.

[0070] Figure 9A shows the behavior of $|\hat{V}_{th}|$ versus real (actual) stress time for Case 3. Here the magnitude of the stress voltage was increased to 4.7 V at 140°C so that the values of $|\hat{V}_{th}|$ become more significant than in previous cases. For this third case, first an "ON" stress (A) was applied for a duration of 900 seconds with readouts at 20, 180, and 900 seconds. The configuration was then switched to an "OFF" stress (B), still at 4.7 V and 140°C for a total duration of 900 seconds (measured from the start of the "OFF" stress) with readouts at 20, 180, and 900 seconds. This procedure of an "ON" stress followed by an "OFF" stress, each for a duration of 900 seconds, was repeated four more times for a total of five cycles of "ON" followed by "OFF" stresses (A' - B'''). Thus, for Case 3, the period \bar{t}_s was 1800 seconds and the duty factor was 0.5 versus 0.13 for Case 2 and 0.016 for Case 1.

[0071] In Figure 9B the behavior of $|\hat{V}_{th}|$ for the first readouts (three readouts represented by open circles in Figures 9A and 9B during the "ON" stress, up to and

including time at 900 seconds, are modeled by a straight line 90 on a log-log scale as predicted by equation (1), with $n = 0.31$ (same as for case 2 during the "ON" stress), which is the time exponent factor for the power law relationship between $|\hat{V}_{th}|$ and time. The four readouts for the "ON" stresses following the "OFF" stresses (triangles in Figure 9B), however, again show a different behavior. As shown in Figure 9B the straight line model 91 representing the "ON" stresses following the "OFF" stresses have a shallower slope with a time exponent factor of 0.25 versus 0.31 for the case where the "ON" stress was not proceeded with an "OFF" stress. Also, another significant observation is made, which is that the time exponent factor for "ON" stresses when proceeded with "OFF" stresses decreased from 0.46 for Case 2 to 0.25 for Case 3, and in this last case the exponent was less than 0.31, which is the value obtained when the "ON" stresses were not interrupted by "OFF" stressing. The conclusion for the data is that, again, the effect of the "ON" stressing followed by "OFF" stressing, depending on the exact conditions of time intervals and duty factors, may lead to a higher or lower net $|\hat{V}_{th}|$ than what is predicted by "ON" stressing alone without interruptions by "OFF" stressing.

[0072] Finally, a fourth case is presented, this time using pulsed voltage conditions at a frequency of 2.5 MHz and a duty factor of 0.5 (similar to Case 3) to simulate actual operating conditions for an inverter to investigate the AC behavior of the PFET degradation due to the NBTI mechanism.

[0073] Figure 10 shows the AC pulsed stress configuration for the PFET 10. Drain 14 and n-well 12 are kept at constant potential 103 of +4.7 V. Source 13 receives input waveform 101 of pulses. Gate 15 receives input waveform 102 of pulses out of phase with the source input waveform.

[0074] Figure 11 shows the behavior of $|\hat{V}_{th}|$ as measured at various readouts 111 for the PFET under the AC pulsed stressing with the X-axis as the effective time under "ON" stress condition, which means that the intervals of "OFF" stressing (50% of real time for each cycle) were not included. Figure 11 also includes the data 112 in Case 3 for the condition where the "ON" stressing was not interrupted by "OFF" stressing. As indicated in Figure 11, the time exponent factor for the AC pulsed stress configuration is 0.43, which is higher than the exponent factor for the DC "ON" stress (0.31). This

result indicates that under these conditions, the AC pulsed stress configuration over time gives a net higher $|I_{th}^{V_{th}}|$ than predicted by DC stressing.

[0075] It is concluded from all the cases investigated above that the actual degradation of the PFET due to the NBTI mechanism, under AC pulsed conditions, shows a more complicated behavior than what would be predicted by DC stressing alone. For this reason it is important to design a system which can accurately measure the effect of the NBTI mechanism on the performance of CMOS circuits, under actual operating conditions of frequency, duty factors, and technology/processing interactions. It is also important that this system be capable of investigating the effect of changes in the operating conditions like frequency and duty factor. In the system employed in this art, which will now be introduced, the output pulse delay is the measurement for the effect of the NBTI mechanism on the circuit performance.

[0076] The circuit of the present invention uses self-resetting dynamic logic to create a pulse propagator circuit for the evaluation of the effect of duty cycle on circuit performance. This pulse propagator incorporates a programmable reset delay to vary the propagated pulse width from approximately 20% to 80% of the total cycle time.

[0077] Figure 12 illustrates the top-level circuit elements which form the pulse propagator circuit 120 which is a first exemplary embodiment of the present invention. This circuit may be compared to a ring oscillator. In a ring oscillator, an odd number of inverter stages are connected in an infinite loop. The odd number of inverters causes the output of each inverter stage to oscillate at a fixed duty cycle. The duty cycle of a ring oscillator is generally very close to 50% and is not programmable.

[0078] Like a ring oscillator, the pulse propagator 120 operates as an infinite loop since node OUT24, the output of the last propagator stage BUF24 (121), is also the input to BUF0, the first propagator stage 122. Unlike a ring oscillator, however, each stage of the pulse propagator is a non-inverting dynamic buffer stage rather than an inverter. The pulse propagator therefore requires a pulsed START input 123 to cause the first buffer stage 122 to evaluate and propagate a pulse to subsequent buffer stages. Given a single START pulse, the pulse propagator will subsequently oscillate in an infinite loop. The START pulse may be generated externally, or generated on-chip

from an external trigger. Inputs D<1:7> (see label 124) of Figure 12 control the programmable reset delay 125 of the pulse propagator.

[0079] Figure 13 illustrates the operation of the pulse propagator 120 for three different settings of these controls 124. The first wave form 130 ("VESTART/low") provides the START input pulse input 123 shown in Figure 12. The second wave form 131 ("OUT24/low") illustrates the duty cycle of the output when the reset delay is set to a minimum, i.e., D<1:7> = "0000000". The minimum duty factor, as the "OUT24/low" wave form illustrates, is approximately 20%. The third wave form 132 ("OUT24/mid") illustrates the duty cycle of the output when the reset delay is set to the mid point, or D<1:7> = "1111000". The mid point duty factor illustrated by wave form "OUT24/mid" is approximately 50%. The final wave form 133 ("OUT24/high") illustrates the duty cycle of the output when the reset delay is set to the maximum, or D<1:7> = "1111111". The maximum duty factor illustrated by wave form "OUT24/high" is approximately 80%.

[0080] Figure 14 illustrates the dynamic self-resetting buffer circuit element (e.g., 121, 122 of Figure 12) used in the pulse propagator circuit. Prior to propagating a pulse, the RES input is low, causing PFET device T1 to be off and NFET device T0 to be active. Node OUT is low, causing the primary dynamic node to be held high by PFET device T2. When a high-going pulse is applied to node IN, device T3 becomes active, causing the primary dynamic node to evaluate low. Node OUT transitions high during this evaluation. The pulse on node IN then transitions low and node OUT remains high until the RES input pulses high.

[0081] Figure 15 illustrates the programmable reset delay circuit (e.g., 125 in Figure 12). This circuit determines the delay between the high transition of the dynamic self-resetting buffer output and the generation of a reset pulse to restore the buffer for the next pulse propagation. The IN input node of this circuit is connected to the OUT output of the dynamic buffer. The RES output of the programmable delay circuit is the RES input to the dynamic buffer. The programmable delay circuit uses a "thermometer code" delay decode method where D<1:7> = "0000000" is the minimum delay count. Subsequent counts of 1, 2, 3, 4, etc., are of the form "1000000", "1100000", "1111000", and "1111000", respectively. Therefore, the circuit taught in Figures 12-

15 can be used to provide a means to stress and monitor results of the NBTI effect in a representative logic path circuit, as embodied in the Ring Oscillator structure.

[0082] Another circuit 160 which can further expand the level of stress control while providing isolation of the performance path to only that PFET which is stressed for the NBTI effect, is shown in Figure 16 as a second exemplary embodiment of the present invention. The target device 161 is a PFET (labeled T0) which can be isolated as per the truth table shown in the figure for DC, AC, or free-run stress configurations. Then with the proper input levels as per the truth table 162, each such circuit 160, 160' shown in Figure 16 can be electrically interconnected to a neighbor into a ring oscillator 170 shown in Figure 17, which allows a measurement of pre- and post-stress frequencies to be compared.

[0083] Figure 18 shows an example of such waveforms for this circuit in which a pre-stress wave form 1801 is superimposed on post-stress wave form 1802. Note that the oscillator runs at 250 + Mhz in its pre-stress operation. This performance is well in the range of today's high performance digital circuits.

[0084] The requirements for the highest degree of stress flexibility and applicability are:

[0085] 1.) Ring oscillator circuit which is used to measure pre/post stress period.

[0086] 2.) Ring oscillator circuit in which a single PFET per stage is in the performance path.

[0087] 3.) A test means by which said PFET per stage can be isolated from the ring oscillator circuit structure.

[0088] 4.) A test means by which said PFET per stage can be stressed in a DC on/off mode.

[0089] 5.) An alternate test means by which said PFET can be stressed in an AC mode by applying a gate pulse of selectable frequency and/or duty factor.

[0090] 6.) A test means by which said PFET having been either DC, AC, a combination of DC and AC stresses, or a free-run stress can then be electrically reconnected into the ring oscillator circuit.

[0091] 7.) The ring oscillator frequency shift then being correlated to a V_{th} shift previously determined by stress of identical PFET devices.

[0092] 8.) The Ring Oscillator frequency shift being correlated to a V_{th} shift determined by sample measurement of said PFET devices via probe pads S1-S4 as shown on Figure 17.

[0093] Figure 18 shows the output of the ring oscillator 170 of Figure 17, which is constructed from nine stages of the circuit 160 shown in Figure 16. The Pre-stress frequency of this oscillator runs at 258 Mhz for typical process and voltage, at 85C. The nine stages are then stressed in parallel as per the truth table in Figure 16. Assuming that $\Delta V_{th} = -100 \text{ mV}$ in each target device in each stage, in response to a given stress, the oscillator frequency is shown to slow to 225 MHz. This is a reduction of nearly 14 %. Therefore a circuit means is shown which allows the unambiguous stress and characterization of the NBTI effect in P+ gated PFETs.

[0094] The circuit shown in Figure 16 consists of the target device (T0), the I/O pins (SOURCE, GATE, VPP, IN, DRAIN and OUT) and the stress control pins (bSTRESS1, bSTRESS2). The gate path of target device T0 is controlled by the bSTRESS2 input. The drain path is controlled by bSTRESS1. The SOURCE is directly accessed from the pads of the test site on which the overall circuit (Figure 17) would reside.

[0095] DC.Stress Conditions:

[0096] As per the truth table 162 on Figure 16, if an "ON" stress (GATE = 0, SOURCE = DRAIN = 1) as in Figure 1 of disclosure is desired, the bSTRESS2 input is tied LOW. This turns OFF device T3 and isolates PFET T0 gate (net034) from the ring oscillator path. At the same time, device T6 turns OFF and T5 charges the gate of pass gate T4 to VPP, thus connecting T0 gate to the GATE input pin.

[0097] Also, the bSTRESS1 input is tied LOW. This turns device T2 OFF and enables TRIBUF_0. With the DRAIN input HIGH, the drain of T0 (OUT) is held high. With SOURCE held HIGH from it's pad, the target PFET device T0 is in the "ON" DC stress configuration. An alternating ON/ OFF DC stress can also be applied in this mode by switching the GATE to a HIGH level and switching the SOURCE and DRAIN inputs to the LOW level after the desired time under ON Stress has been met. The device can then

be held in the OFF stress for the desired duration until the GATE, SOURCE, DRAIN could be switched again to the ON state stress. All stages of the ring oscillator then see this stress in parallel. Subsequent bias of the ring oscillator inputs to Free Run mode then allow measurement of the oscillator frequency and the effect of the stress.

[0098] AC Stress Conditions:

[0099] An AC Stress which simulates the AC biases of the device in the Free Running ring oscillator, can be run as per the truth table 162 in Figure 16. In this mode, devices T0, T1, T2 operate as an inverter, isolated from the ring oscillator connectivity. The inverter AC operation now allows the target device to be stressed in an NBTI AC mode. This mode is activated by the application of a LOW level to bSTRESS2 as for the DC Stress mode. This again results in control of T0 gate from the GATE input through device T4. The SOURCE is held HIGH. The bSTRESS1 input is also held HIGH. This puts the TRIBUF in Tri-state while turning device T2 ON, creating the inverter discharge path through device T1. The DRAIN input is also held high to turn the TRIBUF PFET stack OFF. The GATE input can then be toggled at the desired frequency and/or duty factor as controlled from the test site pads. Subsequent bias of the Ring Oscillator inputs to Free Run mode then allow measurement of the oscillator frequency and the effect of the stress. The Free Run mode can also be used alone as a stress configuration.

[0100] The goal of the enhanced NBTI stress and characterization circuit is to provide for the unambiguous stress and characterization of the target PFET. As such, this PFET is designed as a narrow width/long channel device, in keeping with preliminary results showing these devices to be most susceptible to the NBTI effect. This then creates the further requirement of using small geometry devices in the ring oscillator in order to provide for high frequency operation via minimization of oscillator stage loads. Other circuits designed with wider/shorter devices could be useful to verify the NBTI effect in those devices without departing from the intent of this invention.

[0101] Hence, since it is required that a single target device be uniquely stressed, all pass gate logic in the ring oscillator path must be made with NFETs as per devices T1, T2 and T3. Devices T2 and T3 may be designed with minimum channel devices, since they will see low Vds values during their charging/discharging of their respective

nodes. This then minimizes the potential for channel hot carrier effects that could result in unintended NFET V_{th} shifts, which could then make stress results non-unique. For this case, device T1 has its channel increased from the 120 nm minimum.

[0102] The Channel Hot Carrier (CHC) concern is also addressed for the target PFET T0 in the AC stress mode. Since the target device is 500 nm long, the CHC effect will be reduced exponentially. Also, the isolation of the output (OUT) from the input of the next stage (n+1) due to its input device T3 being off, allows the rapid rise time/fall time (t_R/t_F) of the node OUT. Rapid t_R/t_F results in low V_{ds} duration during the AC stress, further eliminating the CHC effect.

[0103] Figure 19 shows one example of how the present invention can be used to further investigate the NBTI phenomena. The example demonstrates how the invention could be used to correlate a change in threshold voltage, under the application of a DC stress, to a change in frequency of the ring oscillator taught in this invention. Other examples should be obvious to a person of ordinary skill in the art.

[0104] In Figure 19, the PFET under evaluation is incorporated into the circuit of the present invention. In step 1901 the initial threshold voltage V_{th0} and initial frequency of the ring oscillator f_0 are measured. This PFET device is then subjected in step 1902 to a DC stress test by subjecting it to preselected test values including values for V_g , V_d , and V_s , and the change in threshold voltage (\hat{V}_{th}) due to DC stress is determined. In step 1903 the oscillation frequency f_1 of the ring oscillator following the DC stress is determined, from which the change in frequency (\hat{f}) due to the DC stress is calculated. The measurements allow a calculation and correlation of \hat{V}_{th} and \hat{f} (step 1904). Thereinafter, the parameters can be changed (step 1905) and the DC stress repeated as desired. The final results, with all measurements using desired conditions of voltage, temperature and stress time having been completed, should yield the following constants of the \hat{V}_{th} model: \hat{H} , $\hat{\beta}$, and n .

[0105] Figure 20 shows one example of how the present invention can be used to further investigate the NBTI phenomena. The example demonstrates how the invention could be used to correlate a change in PFET threshold voltage, under the application of an AC stress, to change in frequency of the ring oscillator taught in this invention. Also Figure 20 shows one example of how the present invention can be employed for

reliability manufacturing in-line control of hardware using the measured change in frequency of the ring oscillator due to an AC stress. Other examples should be obvious to a person of ordinary skill in the art.

[0106] In Figure 20 the PFET under evaluation is incorporated into the circuit of the present invention. In step 2001 the initial threshold voltage V_{th0} and initial frequency of the ring oscillator f_0 are measured. This PFET device is then subjected in step 2002 to an AC stress test by subjecting it to preselected test values including values for frequency, duty factor DF, stress time, and stress voltage V_g . The change in threshold voltage \hat{V}_{th} due to AC stress is determined. In step 2003 the oscillation frequency following the DC stress f_1 is determined, from which the change in frequency due to DC stress (\hat{f}) is calculated. The measurements allow a calculation and correlation of \hat{V}_{th} and \hat{f} (step 2004).

[0107] From this correlation, a constant B is determined, whose significance will be shortly described (equation 4). Also in step 2007 conditions for frequency, duty factor, and stress times can be changed, and the constants A and n_1 are determined, where A is a constant associated with the AC stress and n_1 is the time exponent under AC stress conditions (equation 2 will be discussed shortly). In step 2005 the change in frequency \hat{f} is compared with predetermined maximum allowed value or values based on preexisting specifications. In step 2006 the preset procedures for manufacturing in-line control are applied and a decision is made whether or not to accept the hardware.

[0108] To further develop the model for NBTI in accordance with the present invention, the results of the testing and AC stressing of the circuit utilized in this system are then expressed in the following bench mark model:

[0109]

$$\Delta V_{th}(AC) = A \times e^{(-\Delta H / kT)} \times (W)^{-m} \times \Delta V_{th}(CYCLE) \times t_{eq}^{n_1} \quad (\text{Equation 2})$$

[0110]

Equation 2 gives the method of calculating $\hat{V}_{th}(AC)$ which is the change in threshold voltage of a PFET in a preselected circuit under any desired AC application

conditions. In the above equation, \hat{H} is again the activation energy determined from the system measured degradation (\hat{f}) at different temperatures. The factor m is determined from the dependence of the degradation on PFET device width (AC mode), and typically has a value of about 0.1 or less, n_1 is the time exponent under AC stress conditions. T is the operating temperature of interest and K is Boltzmann's constant. A is a constant depending on the specific technology and its integral effect on the NBTI degradation mechanism. The constants A and n_1 , which are the degradation constants under AC stress conditions, are determined according to the procedure described in the flowchart in Figure 20.

[0111] The term \hat{V}_{th} (CYCLE) is the average effect, measured over one cycle, of the exponential effect of gate voltage, and is given by:

[0112]

$$\Delta V_{th}(\text{CYCLE}) = (1/V_n) \times \int_0^{V_n} e^{(-\gamma T_{ox}/V_g)} dV_g \quad (\text{Equation 3})$$

[0113] where V_n is the intended voltage for circuit applications, \hat{V} is the voltage acceleration determined from measuring the circuit degradation (\hat{f}) at different supply voltages, as shown in Figure 19. T_{ox} is the electrical effective oxide thickness for the technology in question. V_g is the gate voltage under AC stress described in the flowchart of Figure 20. The integration is carried out only in the situations where that gate voltage is lower than the voltage of either or both of the source and drain voltages, i.e., only when the NBTI mechanism is active. Otherwise, no integration is carried out for other parts of the cycle time where this condition is not present.

[0114] The equivalent stress time over the intended useful life time for the applications t_{eq} is given by:

[0115]

$$t_{eq} = B \times (f_{sw} f_{cl}) t_{use} \quad (\text{Equation 4})$$

[0116]

Here, B is a constant determined from the results of the flowchart in Figure 20, based on the degradation measured at different values of duty factor in the range of

interest of the frequency for the circuit application in question. f_{sw} is the average switching frequency for the gate voltage to be lower than the voltage of either or both of the source and drain diffusions. f_{cl} is the clock frequency and t_{use} is the actual use time. The exponent $n1$ is determined from the method shown in Figure 20 by comparing the degradation results at different AC stress times. The parameters t_{use} , f_{cl} , and f_{sw} are predetermined from intended application conditions of the circuit in question.

[0117] The present invention provides a method of determining the magnitude and behavior of the degradation due to the NBTI mechanism under any desired AC conditions of voltage, duty factor, and frequency of any intended circuit applications. It also permits a determination of the difference between the degradation due to the NBTI mechanism under DC and AC conditions.

[0118] The present invention also provides a way to determine the effect of the degradation due to the NBTI mechanism on technology scaling under actual AC operating conditions and from which an optimum and realistic path for technology scaling could be arrived at. It also provides a procedure and methodology according to which a reliability in-line manufacturing control system is achieved to protect manufactured goods from any undesired degradation due to the NBTI mechanism.

[0119] While the invention has been described in terms of a single preferred embodiment, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the appended claims.